Wetting and Drying Compacted Soil-Lime Mixtures

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Abstract. Soil treatment technique with lime is widely applied in the world in the field of earthworks. It allows reuse of materials useless for implementation embankments. But the lack of knowledge of behavior of cycles, drying/wetting in terms of volume and water change, the mechanical performance of the treated soils, the optimal lime dosage are the origin of the limited application of this technique to embankment and the no mentioned in the GTS (technical Guide soil treatment with lime and/or hydraulic binders) of this technique. The soil studied is A-4. Lime dosages are chosen based on two objectives: the amelioration and stabilization to cycles drying/wetting of soil.

Keywords: Soil · Treatment · Lime · Cycles wetting/drying · Stabilization

1 Introduction

The soil with lime treatment is a technique widely used in the field of Earthworks (road, rail, airport infrastructure, platforms, and others.) since 20 years ago. It is now considered a classic technique to reuse unsuitable soils (generally, the fine limono clay soils) in the construction of embankments as well for minor roads for heavy infrastructure (highways, high-speed lines, airports, and others.). The goal of the use of this technique is to drying the soil, improve her manipulation and the establishment of compaction, to reach the capacity required. In addition, the soil with lime treatment to stabilize slopes and embankments. This technic have double impact, the first to improve soil properties (short term) and the second to stabilize the soil (in the medium and long term).

Lime stabilization is one of the most economical techniques for improving the engineering behavior of clayey soils (Ingles and Metcalf 1973; Little 1995; Paige-Green 2008; Lemaire et al. 2013). The addition of lime to soil causes two basic sets of reactions, one being a short-term reaction while the second is a long-term reaction (Little 1995). The immediate effect of lime addition is to cause flocculation and agglomeration of the clay particles caused by cation exchange at the surface of the soil particles. The result of this short-term reaction is mainly to improve workability and plasticity (Little 1995; Mathew and Rao 1997). The long-term reactions may

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require weeks, months or even years to complete, depending on the rate of chemical decomposition and hydration of the silicates and aluminates. This results in the formation of cementitious materials, which bind the soil particles together and improve the mechanical properties of the lime treated soil.

This present study the behavior of soil treated with lime face-to-face to wetting-drying cycles.

2 Materials

2.1 Materials

The soil samples used were collected from Khelil de Bordj Bou Arréridj (Algeria). (Tables 1, 2) and (Fig. 1) give the identification test results carried out on these soil samples and their chemical composition respectively. According to standard ***ASTM D3282-73*** the soil used in this study is classified in class **A-4**.

Table 1. Geotechnical properties of khelil soil (A-4).

Parameters	Symbols	Range of variation	Mean values
Liquid limit	WL (%)	41.203–41.831	41.525
Plastic limit	WP (%)	29.024–29.911	29.307
Plasticity index	IP (%)	12.179–12.255	12.218
Methylene blue value	MBV	1.590–1.623	1.568
Over to 2 mm	% 2 mm	90.9–92.8	91.534
Over to 0.08 mm	% <0.08 mm	65.9–68.7	67.10
Clay content	C2 μm (%)	4.274	4.274
Activity of clay	Ac	2.850–2.867	2.859
Optimum water content	Wopt (%)	22.274–22.321	22.300
Maximum dry density	γd-max	15.710–15.990	15.880

Table 2. Chemical composition of khelil soil (A-4).

Constituents	SiO_2	AlO_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	Cl
%	31.43	4.19	1.22	32.5	1.89	0.36	0.40	0.04	0.01

Quicklime used comes from ERCO's company of Hassasna, wilaya of Saïda (Table 3).

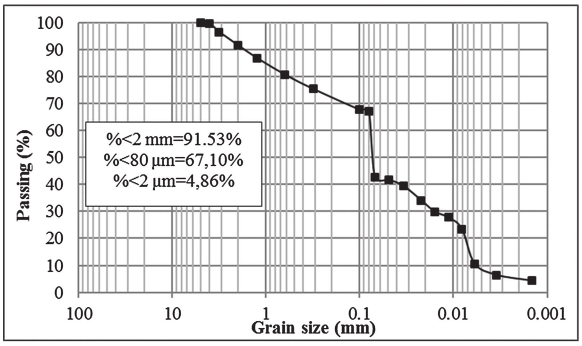

Fig. 1. Grain size distribution curve of soil A-4.

Table 3. Physico-chemical properties of Saida's Quicklime

Designation	BMSD
Chemical composition CaO	82,77
MgO	1,83
Fe_2O_3	0,87
Al_2O_3	3,27
SiO_2	1,35
SO_3	0,11
K_2O	0,151
Na_2O	0,064
Insolubles in Hcl	<1,00
Physical properties Bulk Density	731 g/l

3 Results and Discussion

In the following, we proceed to the analysis, the interpretation and the presentation of the results obtained in the study. The properties studied are: The point of fixation of lime **(PFL)**, the liquid limit **(LL)**, the plastic limit **(PL)** and plasticity index **(IP)**, Methylene blue value **(MBV)**, normal Proctor compaction **(γd, Wopn)**, Unconfined compressive strength **(UCS)**, ultrasonic pulse velocity **(km/sec)** and wetting–drying cycles.

These tests were carried out on untreated soil (control sample) and on treated soil with a mixture of various lime contents (Table 4).

3.1 The Point of Fixation of Lime (PFL)

The attachment point of the lime (PFL), proposed by Hilt and Davidson (1960), is the parameter for estimating the dosage of lime to transition between improvement and stabilization. It corresponds to the dosage of lime to the beyond which there is more

Table 4. Physico-chemical properties of the treated soil

Parameters	0%	1%	3%	5%	7%
pH	11.17	12.49	12.76	12.79	12.78
LL (%)	41.203–41.831	45.809–45.424	42.722–43.114	41.676–42.234	42.325–42.900
	41.525	45.621	41.915	41.953	42.617
PL (%)	29.024–29.911	31.991–32.430	35.036–35.616	35.142–35.739	38.138–38.762
	29.307	32.222	35.326	35.444	38.447
PI (%)	12.179–12.255	13.179–13.818	7.290–8.078	5.937–7.092	3.563–4.770
	12.218	13.399	7.589	6.509	4.170
MBV	1.590–1.623	1.484–1.567	1.132–1.245	1.070–1.150	0.817–0.934
	1.568	1.526	1.200	1.110	0.869
Wopt (%)	22.274–22.321	24.034–24.157	24.178–24.214	26.741–27.058	26.689–26.921
	22.300	24.100	24.200	26.900	26.800
γd-max	15.710–15.990	15.070–15.260	14.760–14.880	14.630–14.710	14.510–14.590
	15.880	15.140	14.830	14.680	14.560
ρd-max/Wopt	0.0711–0.0713	0.0657–0.0661	0.0656–0.0657	0.0587–0.0594	0.0590–0.0595
	0.0712	0.0659	0.0656	0.0590	0.0593

change of limit of plasticity. When the dosage of lime exceeds this dosage, the lime is adsorbed by clay minerals and becomes available for Pozzolanic reactions. The PFL is determined by the test of pH of the soil-lime mixture described in the standard **ASTM D6276-99A** that originated in the study of Eades and Grim (1960). This method allows determining the minimum dosage in lime so that the soil-lime mixture reaches a level of pH equal to 12.4. From this pH value, additional lime is supposed to be available for the development of the Pozzolanic reactions.

pH testing was performed on the soil **A-4**, and the corresponding point of fixation of lime (PFL) has been estimated at 1% (Fig. 2). Based on this measure and the performance evaluated by the Proctor curves, additions of 1%, 3%, 5% and 7% were chosen, corresponding to the minimum, intermediate and high dosages so that the A-4 soil treatment can meet the 3 objectives: (1) improvement, (2) stabilization and insensitivity to the water, (3) stabilization and resistance wetting–drying cycles.

3.2 Consistency Limits

The increase in the percentage of lime cause a significant reduction on the plasticity index, increasing the plasticity limit and decreasing the liquid limit (Fig. 3). However, the plastic limit shows a higher increase than the reduction of the liquid limit. The same

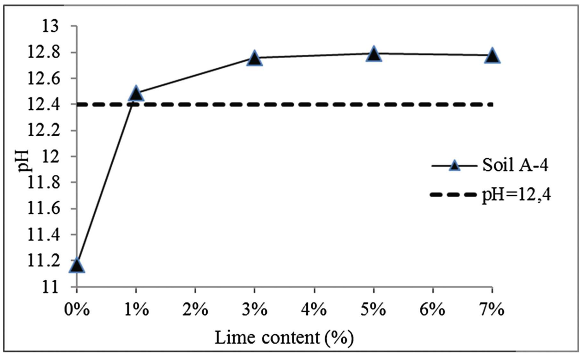

Fig. 2. The point of fixation of lime of soil A-4.

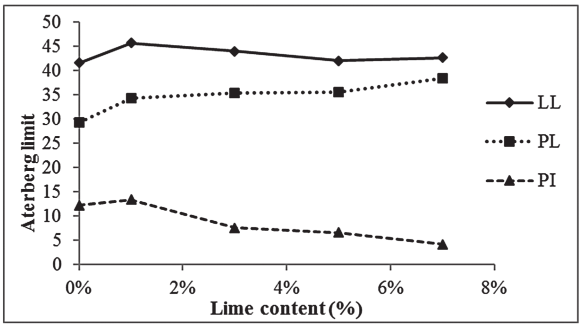

Fig. 3. Consistency limits soil A-4.

results are seen by many researchers (Afes and Didier 1999; Bengraa et al. 2004; Yucel et al. 2007).

Casagrande plasticity chart adapted to expansive soils in accordance with (Dakshanamurthy and Raman 1973 and Chen 1988) can be used to analyze their behavior after the treatment. Atterberg limits test for this soil treated with a mixture of lime indicate again that the liquid limit and plasticity index decrease significantly for treated soil (Fig. 4). It results in a reduction of the plasticity of soil, i.e. a reduction of its high swelling potential from medium to low swelling potential according to (Chen 1988) classification being therefore in the low section at for two classifications. Thus, the soil becomes less sensitive to moisture, so not very expansive and better compactable. Reduction of soil swelling improved stability with regard to deformations due to seasonal changes in the water content and, therefore, a more constant behavior of the compacted soil in what concerns the generating of fine particles.

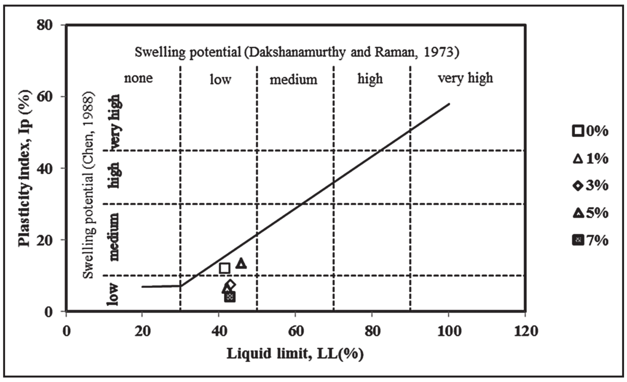

Fig. 4. Classification of soil and the treated soil according to its consistency limits.

3.3 Methylene Blue Value

The methylene blue test is considered as parameter of identification and classification of soils, (**MBV)** and it can be used to estimate the swelling potential of the soil. From (Fig. 5) it is clear that the MBV (i.e. the corresponding Sst = 21MBV) is also affected by the lime contents. In addition, Sst sound mitigation measures seems to indicate that his treatment of mixture of lime reduces its potential of swelling by changing its texture.

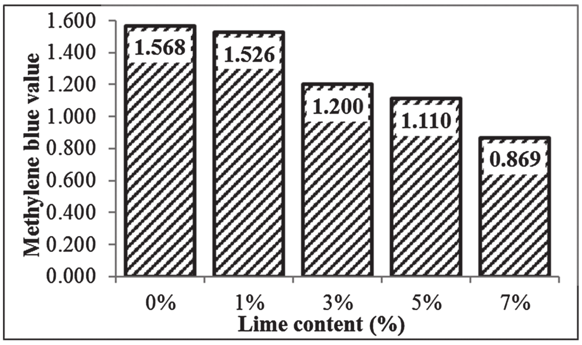

Fig. 5. Methylene blue value of the treated soil.

Results (Fig. 5) show an irreversible behavior, a linear decrease of **MBV** with the increase in the percentage of lime, as showed before for the Atterberg limits. A reduction of 45% was reached with 7% of lime.

3.4 Normal Proctor Compaction

The sensitivity to water mixtures noticed by the shape of the Proctor curves. According to (Fig. 6), the compaction curve of the soil in the natural state give an accentuated shape, which explains the great sensitivity of this soil. For lime contents of 1, 3, 5 and 7% blends, the Proctor curves are to the right and down compared to the curve of the soil control they present a flattened shape, reflecting the low sensitivity of mixtures by water, is all the more marked the soil reacts well with lime.

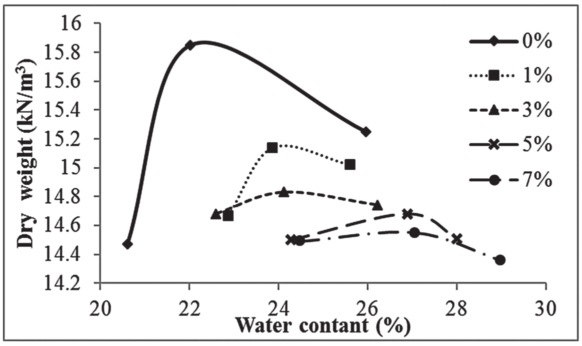

Fig. 6. Normal Proctor compaction.

The variation of the maximum dry density is represented in (Fig. 7). We can see that an increase in the percentage of lime from **1** to **7%** led to a decrease of the dry density at optimum normal proctor **(OPN)** from **15.88** to **14.56 (kN/m^3)**.

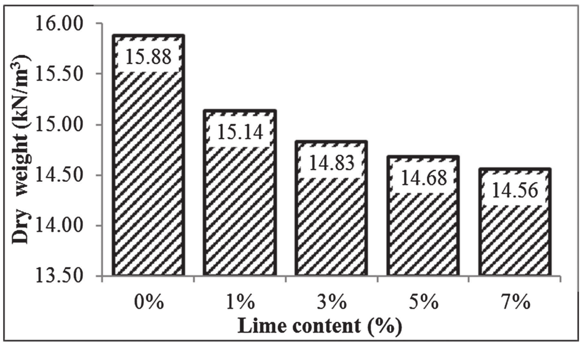

Fig. 7. The variation of the maximum dry density.

Furthermore, since quicklime was used the **OPN** (Fig. 8) water content increases with the percentage of added lime, reaching its maximum value at an **OPN 26.9%** for a percentage of **5%** lime. The treatment of soil with lime reduced the maximum value of the dry apparent density and increases the value of the optimum water content.

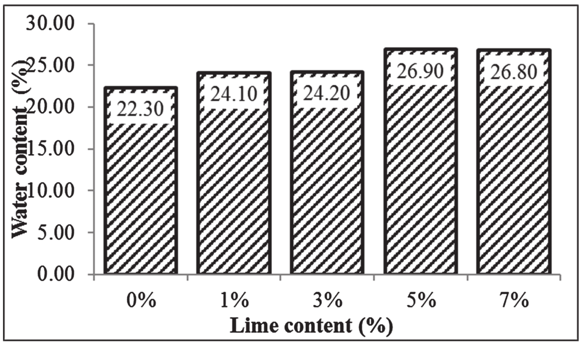

Fig. 8. The variation of the maximum water content.

The optimum water content increasing is due to the reaction of hydration of lime, and then the reason the reduction of the maximum dry density is the low specific weight of lime (Necmi et al. 2007).

After (Fig. 9) normal Proctor compaction tests are conducted on the soil treated with different content of lime in optimal conditions of Proctor. The corresponding test results are a guarantee of good repeatability of the compaction test and indicate a good reconstruction of soils under the conditions for which the massif of soil should be submitted on the spot.

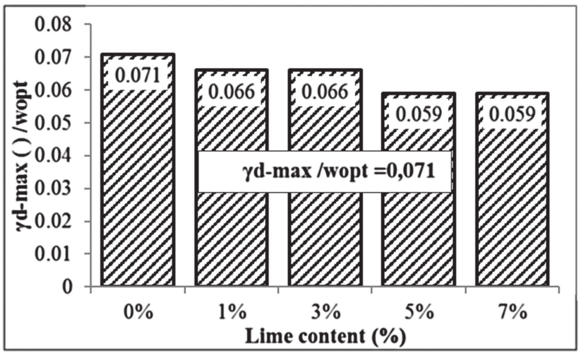

Fig. 9. Lime mixture treatment effect on the normal Proctor compaction test results.

3.5 Unconfined Compressive Strength (UCS)

Figure 10 represents the development of compressive strength based on different conditions of cure for treated and untreated mixtures. It is noticed that at 3 h after treatment, the compressive strength keeps its low value for all the mixtures.

For the period of 28-days of treatment, there is an important development with the increase in the percentage of lime, the strength values obtained for lime content of 1, 3, 5 and 7% are respectively 0.831, 0.839, 0.923 and 0.991 MPa compared with

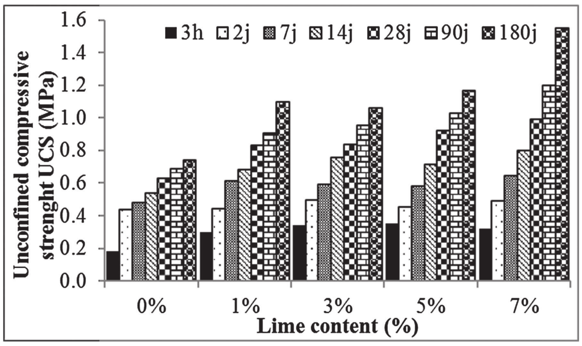

Fig. 10. The variation of the unconfined compressive strength UCS

0.628 MPa for the soil without lime. For the duration of treatment of 90 and 180 days, there is a slight increase in compressive strength to mix (1, 3 and 5) however a remarkable increase the 7% mixture. The same ability of variation is found by several authors (Kolias et al. 2005; Yi et al. 2006).

Compressive strength increases with the increase in the percentage of lime in treated blends, this increase can be explained at early ages by the addition of the fine materials to the soil, which results in better compaction. The reason for the sharp increase in the compressive strength after 28 days is justified by the reaction of hydration of lime during this period (Necmi et al. 2007). An increase in UCS with curing (from 2 to 28 days) between the soil, lime and reactions with the formation of ettringite and/or CAH and CSH. We know that lime improves the compressive strength of the soil by changing the course of hydration of the calcium silicate, which is mainly formed in the early stages of hydration.

3.6 Wave Velocity

The measurement of P waves velocities is one of the non-destructives tests methods to assess the stiffness properties of materials. P wave velocities results (Fig. 11) show

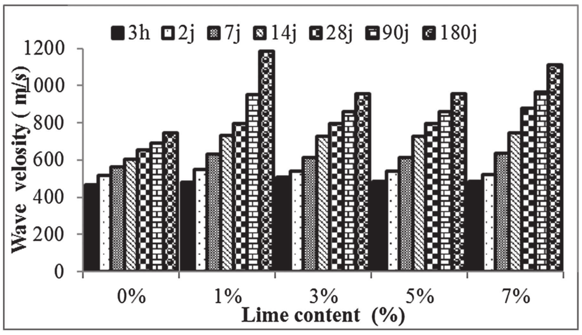

Fig. 11. The variation of the wave velocity P.

similar trends to the results of the UCS tests. For all lime content, the P waves velocities have increased with curing times. After 180 days of hardening, samples of soil with 1, 3, 5 and 7% of lime reaches maximum values of the P wave velocities on the order of 1184, 0957, 0958 and 1110 m/s 0789, 0798, which gives a ratio of improvement of 1.6, 1.3, 1.3, and 1.5 relation to the P wave velocity of the untreated soil samples, respectively. During the reactions occur between the soil and the stabilizing agent (i.e. lime).

Then, the development of a cementitious bonding between soil particles produced by the pozzolanic reaction increases the P-wave velocity measured in the stabilized soil samples. It is known that the P-wave velocity propagation increases as the compaction of the solid increases, in a soil mass, and the amount of voids filled with air and/or water decreases. Similar observations were made for lime-treated clay soil (Al-Mukhtar et al. 2010a, 2010b).

3.7 Correlations of Unconfined Compressive Strength (UCS) and Wave Velocity

Figure 12 shows the relationship between the P-wave velocities and UCS. A good correlation factor (0.8972) demonstrates that the non-destructive P-wave measurements can be considered as an indicator for UCS and can be used in the field to assess the mechanical behavior of soil/lime as shown by several authors for other soil mixtures (Consoli et al. 2012; Rios et al. 2016).

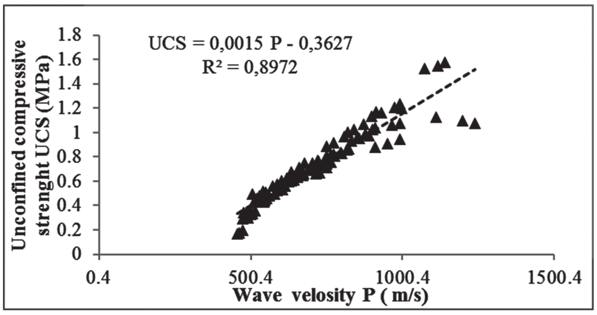

Fig. 12. Correlations of Unconfined compressive strength (UCS) and Wave velocity (P).

The correlation is a linear type:

$$UCS = A(P) + b \tag{1}$$

Previous researches propose a linear correlation between the mechanical strength and wave velocity (Aldaood and Al-Mukhtaret 2014, Viana da Fonseca et al. 2014).

The correlation proposed from the present study in the form:

$$UCS = 0.0015(P) - 0.36271$$
$$R^2 = 0.8972$$

3.8 Impact of Wetting–Drying Cycles

The specimens are prepared with a standard ***ASTM D559 M.***

The changes in volume of the specimens (Fig. 13) were significantly affected by the increase in the number of cycles of wetting-drying in the presence of lime. After 7 days of treatment, volume change has increased slightly, and the shape of the soil samples was retained until the tenth round for the soil with 1% lime (cycle 12 for specimens with 3, 5 and 7%) lost almost 70% of volume for 1% lime and 32.95, 26.38 and 22.68% for 3%, 5% and 7% respectively.

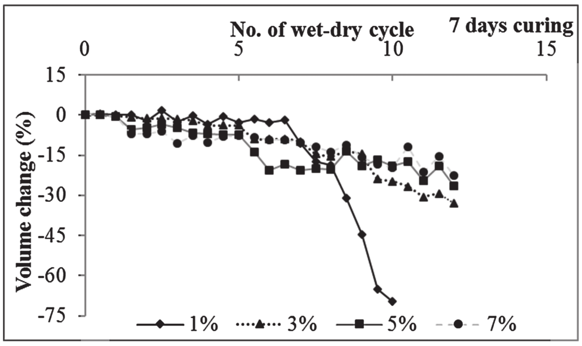

Fig. 13. Volume change with wetting–drying cycles after 7 days curing.

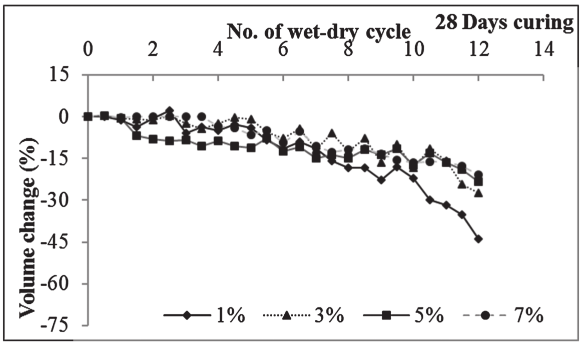

Fig. 14. Volume change with wetting–drying cycles after 28 days curing.

However after 28 days in the treatment sample (Fig. 15) and the shape of soil samples has been preserved up to the last cycle (cycle 12). The specimens lost 43.78, 27.4, 23,405 and 20.99% for 1%, 3%, 5% and 7% respectively. Crack propagation leads to loss in strength and reduction in the volume of soil samples by the disintegration of parts from the cracked samples, later an accelerated deterioration of samples has occurred caused by water penetration into the samples.

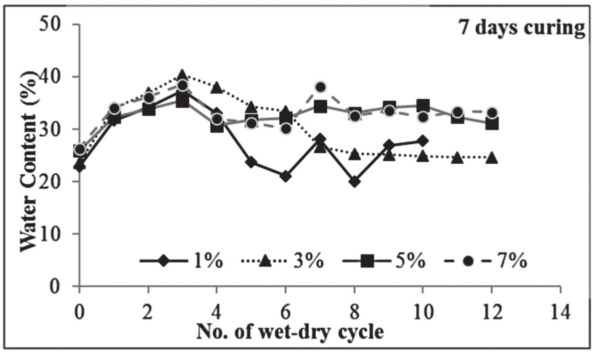

Fig. 15. Water content changes with wetting and drying cycles after 7days curing.

The soil is a porous material and has the capacity of water absorption by capillarity, so to conserve water during the humidification. In this step all empty (micro and macro-pores) were partially saturated, then when the soil samples were subjected to high temperature (70 °C) for 42 h, water inside the pores began escape from samples by evaporation.

The moisture of soils stored for 7 days (Fig. 14) and measured at the end of the drying state was increased during the firsts cycles (4 cycles) that due to the water absorption. From 4^{th} cycle water content remained almost stable for 5% and 7% lime content while it decreased for the initial value in 1% and 3% lime contents.

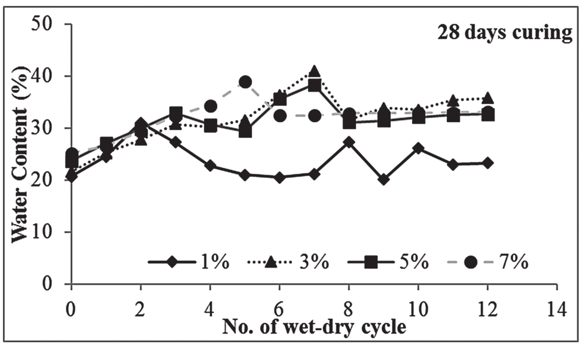

Fig. 16. Water content changes with wetting and drying cycles after 28 days curing.

However, the water content of soils stored at 28 days (Fig. 16) was increased in the first four cycles and even 6 cycles for 7% lime contents. From this cycle the water content remained almost stable for all lime contents except for 1% which decreased to the initial value.

4 Conclusions

After this study, we can draw the following key results: the introduction of lime in the soil has a significant effect on his physical behavior: it was noted a decrease in the plasticity index, a reduction in the Methylene blue value and a flattening of the Proctor curve. The addition of lime brings an immediate improvement in the resistance of the soil by the significant decrease in sensitivity to water. Soil mechanical parameters are clearly influenced by the addition of lime.

- The increase in resistance to compression of treated mixture is well noticed from 28 days. Improving the physical and mechanical behavior can be explained by at short-term (flocculation and agglomeration) and long-term (Pozzolanic reactions).
- The first is a direct, rapid response with immediate effect produced by lime (ground improvement). Lime can then react with clay minerals, causing a flocculation and agglomeration of clays. This flocculation increases the ability to compaction and decreases the plasticity of the soil.
- The second is a slow reaction, which hardens gradually the compacted soil-lime mixture, responsible for long-term (ground stabilization) effects. The alkalinity of the limestone increases the pH of the soil, which releases the aluminates and silicates. These can then react with the calcium provided by lime and water present in the soil which gives two cementation CSH and CAH officers who are responsible to the solidification and hardening the ground.
- The incorporation of lime in the soil increases their behavior with respect to the drying/wetting cycles reducing volume change and keepings the soil shape and the water content.

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